REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 28-10-2011	**2. REPORT TYPE** Briefing Charts	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE **High Energy Advanced Thermal Storage for Spacecraft Solar Thermal Power and Propulsion Systems**		**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) David B. Scharfe, M.P. Young, M.R. Gilpin, and R. Webb		**5d. PROJECT NUMBER** **5f. WORK UNIT NUMBER** 50260542
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RZSA 10 E. Saturn Blvd. Edwards AFB CA 93524-7680		**8. PERFORMING ORGANIZATION REPORT NUMBER** AFRL-RZ-ED-VG-2011-442
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RZS 5 Pollux Drive Edwards AFB CA 93524-7048		**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S NUMBER(S)** AFRL-RZ-ED-VG-2011-442

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited (PA #11935).

13. SUPPLEMENTARY NOTES

For presentation at the JANNAF 2011 Joint Subcommittee Meeting, Huntsville, AL, 5-9 Dec 2011.

14. ABSTRACT

Previous reviews have identified solar thermal propulsion (STP) as a promising candidate for high performance microsatellite missions, due to its high delta-v capability with a quick response time, relatively high thrust and efficiency, and low mass fraction for high capability. However, there are drawbacks to solar thermal propulsion, outlined in this presentation. Augmented STP is proposed and described.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Mr. Marcus P. Young
a. REPORT **Unclassified**	**b. ABSTRACT** **Unclassified**	**c. THIS PAGE** **Unclassified**	SAR	45	**19b. TELEPHONE NUMBER** *(include area code)* N/A

THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

High Energy Advanced Thermal Storage for Spacecraft Solar Thermal Power and Propulsion Systems

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NOTE TO REVIEWERS

- **Please Note:**
  - This presentation is based on the JANNAF conference paper that was sent through the STINFO/approval process:
  - The paper is STINFO # AFRL-RZ-ED-TP-11-412
  - The paper has been approved through AFRL's process and the Public Affairs review. The public Affairs Clearance Number of the paper is 11878.

Outline

- **Motivation – Solar Thermal Propulsion and Microsatellites**
- **Solar Thermal Drawbacks**
- **Augmented Solar Thermal Propulsion**
  - Propellant Requirement
  - Sensible vs. Latent Heat Energy Storage
  - High Temperature Elemental Phase Change Materials
- **Necessary Development Requirements**
- **USC Experimental System**
  - Project Design and Goals
  - Initial Data and Results
- **Conclusions**

Motivation

- **Previous reviews have identified solar thermal propulsion (STP) as a promising candidate for high performance microsatellite missions. [Kennedy 2002, Scharfe 2009]**

    - High *ΔV* capability *with* a quick response time

    - Relatively high thrust and efficiency

Chemical	Solar Thermal	Electric
~230s Isp	*300-700s Isp*	*>1000s Isp*

    - Low mass fraction for high capability

        < 50% $m_{propulsion}$ including propellant for ΔV of 1.5 km/s

Propulsion and *ΔV* for Microsats

- **Microsatellites → Secondary Payload**
  - Remedy sub-optimal orbit insertion
  - Requires 100s to 1000s of m/s *ΔV*

- **Expand the Microsatellite Operating Envelope**

Near Escape Missions: *770-1,770 m/s*
- NEO flybys
- Highly eccentric earth orbits
- LaGrange points
- Earth trailing orbits

GEO Insertion: *~1,760 m/s*
- GTO → GEO

Other Body Capture: *1,110-4,000 m/s*
- Starting from fly-by

May be possible with EP but….
STP offers a much shorter burn time depending on maneuver strategy

Solar Thermal Drawbacks

Without Energy Storage, Output is Illumination Dependent

Thruster operation needs to be de-coupled from illumination

- **Large propellant storage volume utilizing H_2 to achieve ~700s Isp**

  Trade performance for lower volume?

- **Solar thermal requires own concentration system**

  Additional spacecraft component

- **Concentrators must be aimed at the sun for propulsion**

  De-couple optics from s/c orientation?

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- **Large propellant storage volume utilizing H_2 to achieve ~700s Isp**
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→ **Ammonia Propellant**
400s Isp w/ practical storage

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- **Large propellant storage volume utilizing H_2 to achieve ~700s Isp** → **Ammonia Propellant**
  Trade performance for lower volume? — *400s Isp w/ practical storage*

- **Solar thermal requires own concentration system** → **Bi-Modal System**
  Additional spacecraft component — *Thermal-Electric Conversion*

- **Concentrators must be aimed at the sun for propulsion**
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Solar Thermal Drawbacks

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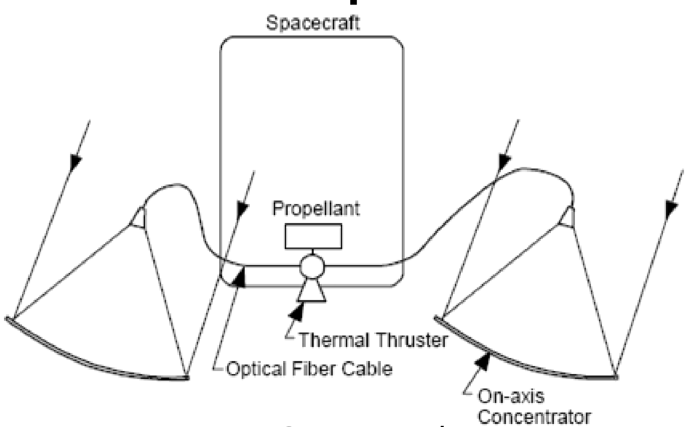
→ **Bi-Modal System**
Thermal-Electric Conversion

- **Concentrators must be aimed at the sun for propulsion**
  De-couple optics from s/c orientation?

→ **Fiber Optics**

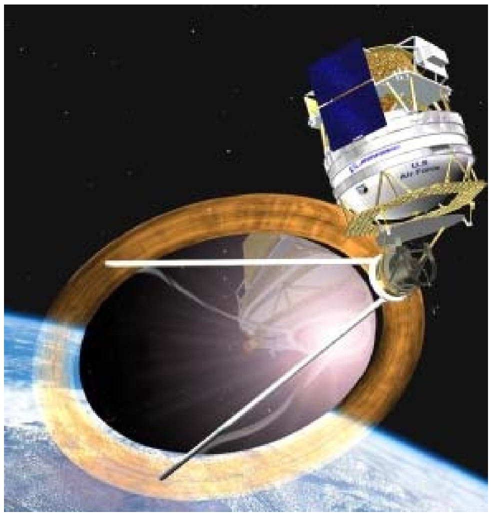


Source: Nakamura

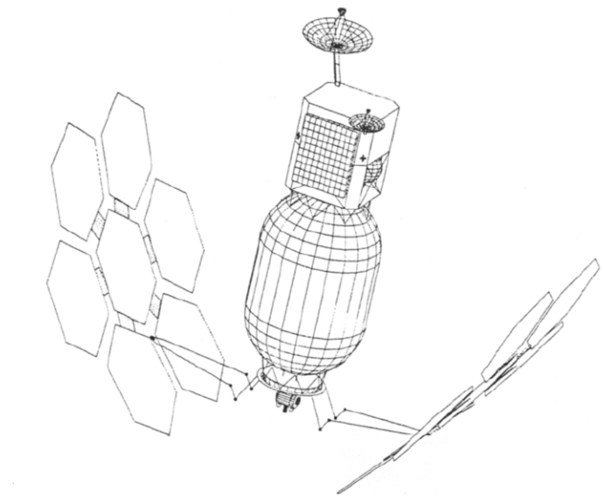
Solar Thermal Projects

Despite major development projects, no STP system has flown

Solar Orbit Transfer Vehicle (SOTV)



Integrated Solar Upper Stage (ISUS)



- **Large Scale Systems**
  H_2 propellant storage
- **Sensible Heat Storage**
  Sensible heat graphite storage
- **Bi-Modal Operation**
  High power thermionic conversion

Optimize thermal energy storage for enhanced capability and microsat scalability?

Augmented STP

Goal: Augment STP with Advanced Thermal Energy Storage

For a 100kg Satellite in LEO	
Thrust	**1 *N***
I_{sp}	**300-400 *s***
Specific Power Density	**> 200 W / *kg***
Elec. P. Available	**100 *W Cont.***
Thermal E. Storage Density	**> 2500 *kJ/kg***

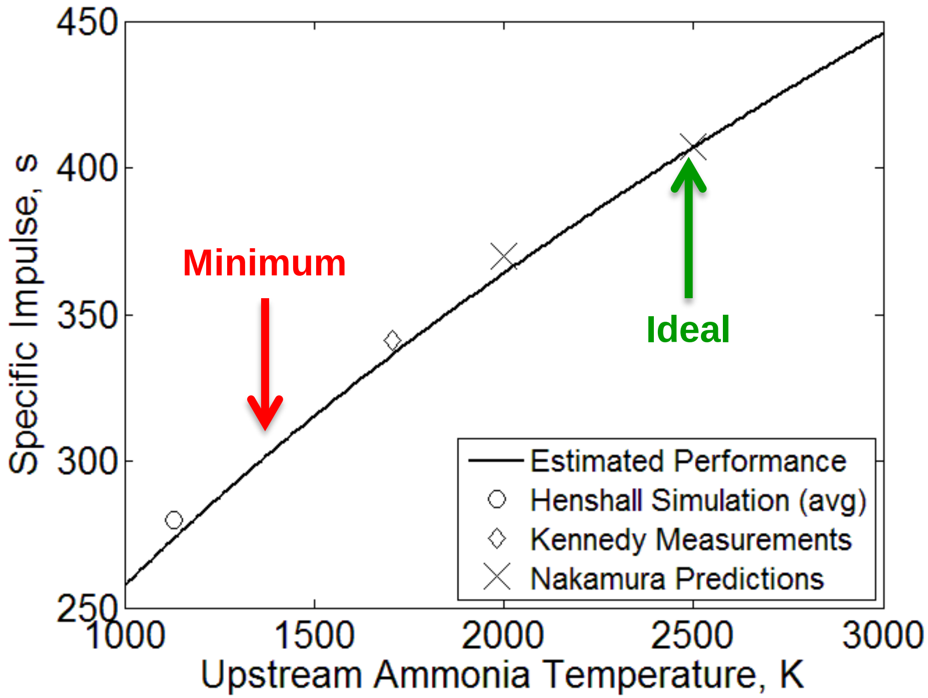
<u>High Energy Density</u>

- **Li-Ion batteries achieve 500 kJ/kg**
  Needs to be on the order of MJ/kg
- **Current PV systems achieve 80 W/kg**
  Needs to achieve greater than 100 W/kg

<u>High Temperature</u>

- **I_{sp} directly tied with temperature**
- **Propellant defines the storage temperature required**

Propulsion Requirement



Ammonia Propellant

- Readily storable vs. H_2
- System can self pressurize
- Dissociation at high T
- Target I_{sp} of 300-400s surpasses small scale chemical systems

Propulsion Requirement Fundamentally Sets Operating Temperature

$$T_{storage} = 2500\ K$$

Solar Concentrator Requirements

For 2500K, a concentration ratio of ~ 10,000:1 is required

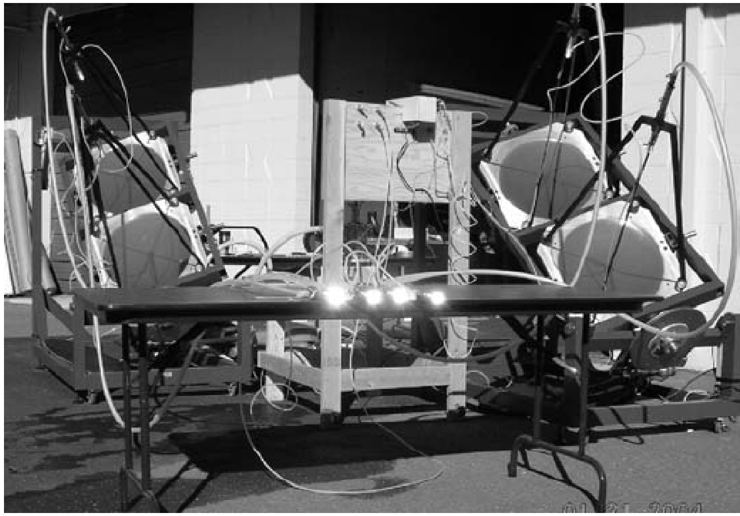
- Both inflatable and rigid designs have been proposed
- $1 kg/m^2$ is commonly achieved
- Small scale concentrators @ $200 g/m^2$ have been shown

Source: Sahara

Source: SRS Technologies

Can De-Couple Orientation via Fiber Optics

- Mass benefit from multiple smaller concentrators
- 70% η_{total} for a space qualified system
- Current lab systems at 35% η_{total}



Source: Nakamura

Sensible Heat Systems

- Requires a high specific heat and a large operating temp range
- Fundamentally large ΔT during operation
- Graphite sensible heat storage was included in the ISUS design

(Solar Millennium Andasol 1 & 2)

Terrestrial Standard

60% $NaNO_3$ + 40% KNO_3

$T_{operation}$ = 560-850 K

ΔT = 280K → 0.42 MJ/kg

Material	T_{melt} [K]	$c_{p,s}$ [kJ/kgK]	$\Delta E/m_{2000\text{-}2600K}$ [MJ/kg]
Carbon	**3923**	**2.09**	**1.25**
B_4C	**2700**	**2.51**	**1.506**
BeO	3010	2.43	1.458
Molybdenum	2890	0.255	0.153
Silicon Carbide	2818	1.47	0.882
Boron Nitride	3273	1.99	1.194

Materials capable of operation at the T_h target

Latent Heat Systems

- Typically Liquid → Solid Transition
- Relatively constant temperature energy delivery
- Consistent thrust performance and tunable electrical energy conversion

Previous evaluations break down materials into 3 categories

Class	ΔH_{fus} [MJ/kg]	T_{melt} [K]	k_{th} [W/mK]
Paraffin Wax	0.072 – 0.214	317 – 379	0.19 – 0.75
Fatty Acids	0.045 – 0.210	268 – 344	0.14 – 0.17
Hydrated Salts	0.115 – 0.492	281 – 1170	0.46 – 5.0

Key Problems

1) Energy Density and k_{th} an order of magnitude too low
2) Melt temperatures too low for spacecraft application
3) Some decompose after repeated cycling
4) Difficulties in storing a molten material

High-T Phase Change Material Considerations

- Properly matched melting temperature
- High energy density

Enabling parameters

- Good material stability
- Manageable material compatibility
- High thermal conductivity
- Low vapor pressure at melting temperature
- Small volume change during transition
- High emissivity

Feasibility requirements

High Temperature Elemental Materials May Fill This Role

High-T Latent Heat Energy Storage

Material	Melting Temp [K]	Heat of fusion [kJ/kg]	Thermal Conductivity [W/mK]
Beryllium	1560	1312	200
Silicon	**1687**	**1785**	**149**
Nickel	1728	298	90.9
Cobalt	1768	272	100
Yttrium	1799	128	17.2
Iron	1811	247	80.4
Scandium	1814	313	15.8
Palladium	1828	157	71.8
Lutetium	1925	126	16.4
Titanium	1941	295	21.9
Zirconium	2128	153	22.7
Chromium	2180	403	93.9
Vanadium	2183	422	30.7
Rhodium	2237	258	150
Boron	**2570**	**4600**	**27.4**
Hafnium	2506	152	23.2
Ruthenium	2607	381	117
Iridium	2739	213	147

Phase-Change TSM - Silicon

- Moderate melting temperature
- Meets microsatellite performance goals
- **330s Isp**
- **1.8 MJ/kg**
- **<2 kg required for target storage**
- **Research/industry familiarity**
- **Radiative output aligned with GaSb/GaAr TPV cells**

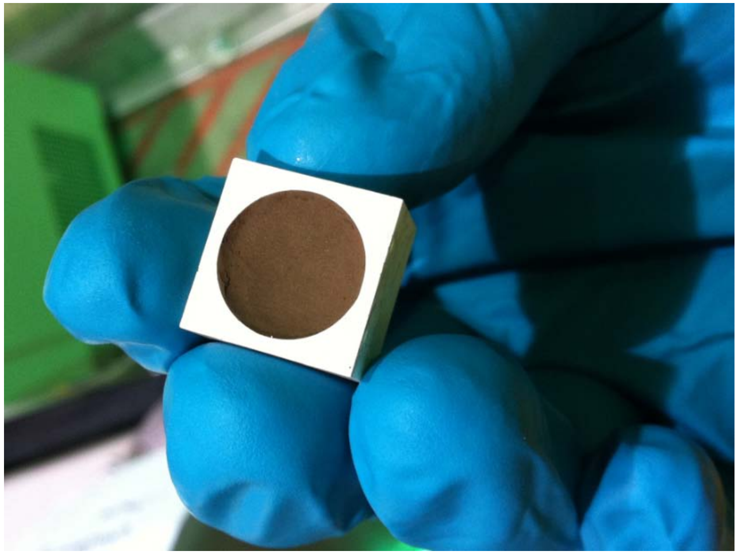
Key Issues

1) Material Compatibilities (chemical/physical)

2) Research/Industry: short-term containment

3) Material compatibilities

Phase-Change TSM - Boron



- Ideal melting temperature
- Meets ideal microsatellite performance goals
- **400s Isp**
- **4.56 MJ/kg**
- **< 1kg Required for target storage**

Key Issues

1) Limited body of research into molten boron

2) Extreme insulation requirements

3) Material compatibilities

4) How to harness the stored energy?

Development Requirements
Electrical Energy Conversion

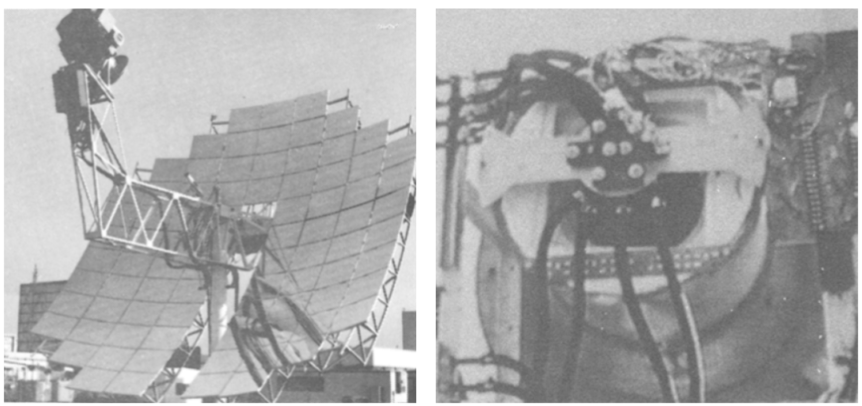
Technology	P_{sp} [W/kg]	Efficiency	T_{max} [K]	Comments
Thermoelectric	9.4	6.3%	1273	• Limited temperature operation. • Incremental development OK for P_{sp} & h.
Thermophotovoltaic	15	>30%	None	• Long lifetime demonstration required. • Operation in space environment required.
Thermionic	100@1kWe	> 10%	2200	• Baselined for another application at higher power levels.
AMTEC	14	16%	1300	• Unlikely to achieve required temperatures.
Nantenna	???	<1%	None	• Significant uncertainties in all aspects. • Current concern: efficient rectifying diode.
Closed Brayton	---	29%	1700	• Possible to achieve required temperatures. • Mass may be high for low power levels.
Free Piston Stirling	100	35%	1050	• Unlikely to achieve required temperatures. • High performance & long lifetime demonstrated.

Development Requirements
Electrical Energy Conversion

Thermophotovoltaics → Strongest Candidate System

McDonnell Douglas

- Designed with *molten silicon* energy storage in mind
- Estimate 25%-40% efficiency



Source: Stone et. al

Edtek

- 25% efficiency pure electric

Source: Edtek

Development Requirements

High Temperature Insulation

Material	Clear	Density [kg/m³]	T_{melt} [K]	$k_{th,500K}$ [W/mK]	$k_{th,1000K}$ [W/mK]	$k_{th,1500K}$ [W/mK]	$k_{th,2000K}$ [W/mK]	$k_{th,2500K}$ [W/mK]
Aerogel[16]	Some	80	600	0.01				
Fused Silica[19]	Yes	2200	1985	1.5	2.1	2.1		
Saphire[18]	Yes	4000	2313	20	8	---	---	
Alumina[18]	No	4000	2345	21	5	5	8	
Boron Carbide[17]	No	2520	2673	12.5	9	6.5	---	---
Silicon Carbide[21]	Yes	3210	3003	120	60	38	28	---
Boron Nitride[18]	Some	3487	3246	37	22	21	19	---
Carbon Bonded Carbon Fiber[20]	No	180	3273	---	0.4	---	0.9	---
Vacuum [Δx=1cm]	Yes	---	---	0.15	0.80	2.39	5.33	10.1

- **Must operate between 1,500 – 2,500 K**
- **CBCF is a promising candidate material**
  - Used in NASA RTG development
  - Estimate 1.4kg of insulation for 1kg of molten boron
- **Vacuum gap with reflective surface is typical first stage in thermophotovoltaic systems**

High Temperature Receiver + Convective Heating

Integrated Solar Upper Stage (ISUS) – NASA/AFRL 1990s

- Bi-Modal system for large satellites at a TRL level of 6
- Utilized thermionic converters and H_2 propellant

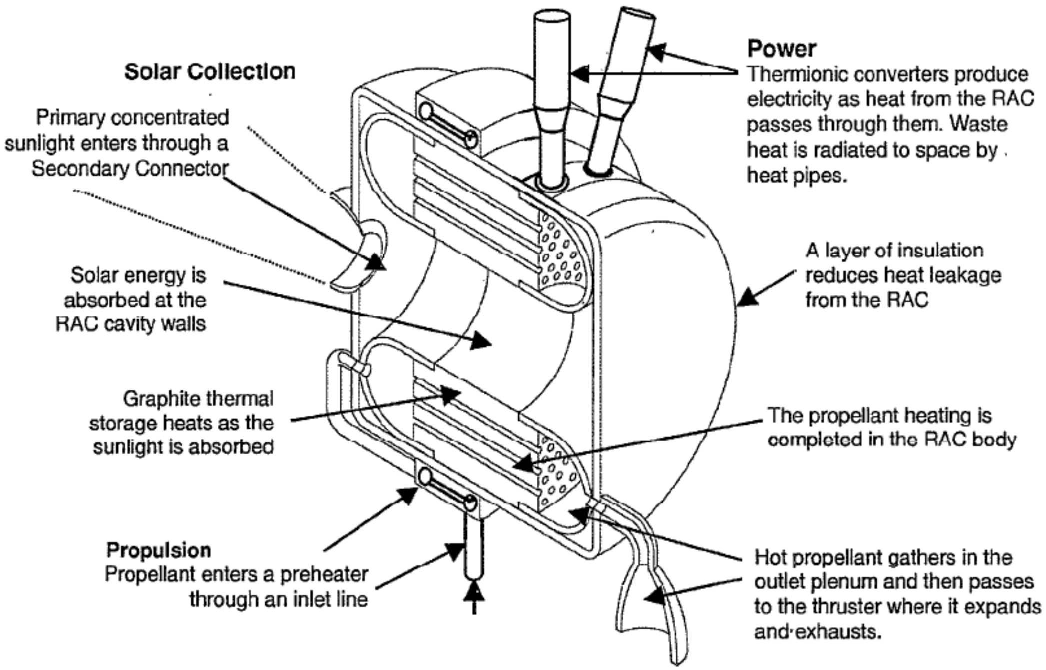


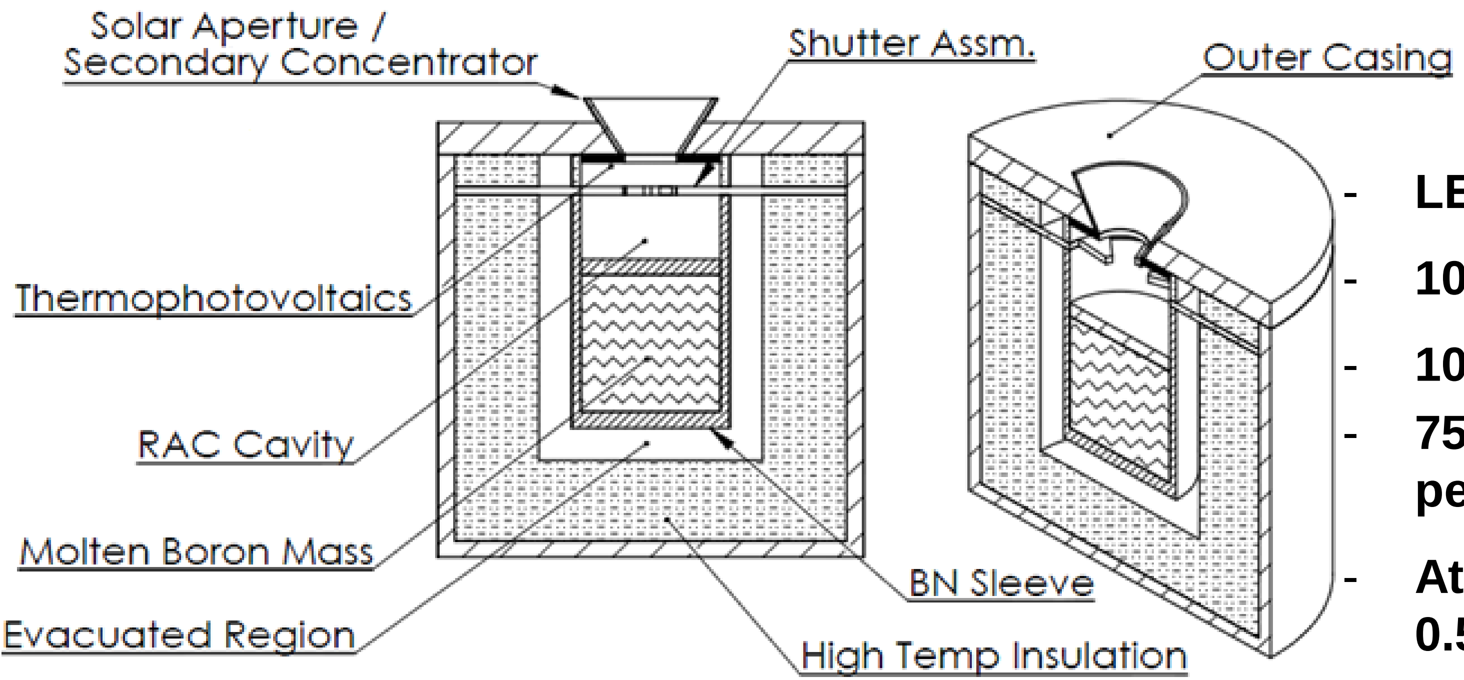
Figure 8. RAC Subsystem Schematic

- ➢ Graphite (rhenium coated) sensible thermal energy storage
- ➢ Highly effective heat exchanger design
- ➢ Higher flux of propellant than possible with direct radiative heating

Preliminary RAC Design

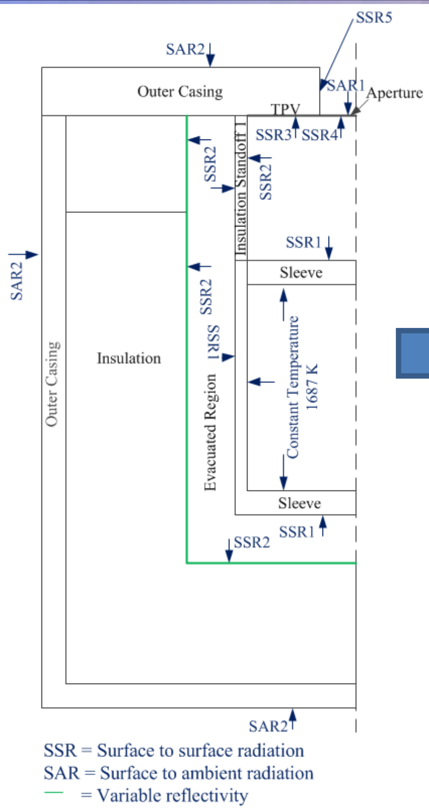
Many Developmental Requirements Have Already Been Investigated

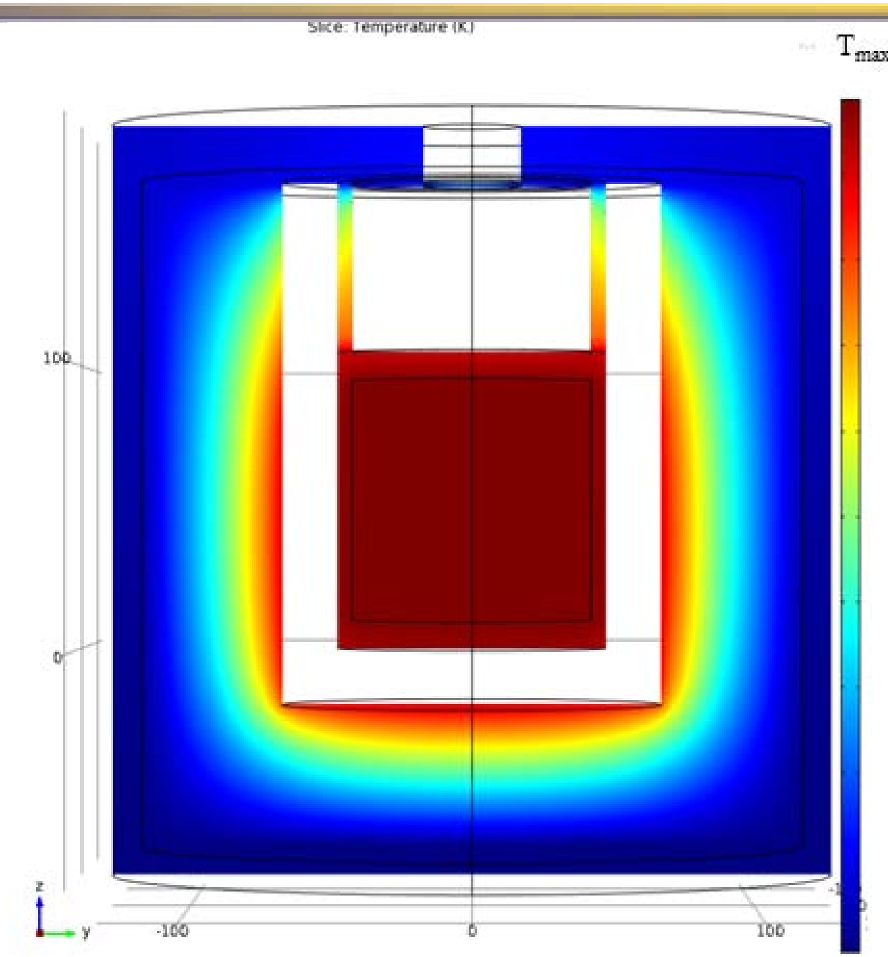
- Initial RAC for use in COMSOL investigation and design comparison



- LEO Operation
- 100 W Thermal Draw
- 100 W Electrical Draw
- 75% energy retention per cycle
- At 20% $\eta_{conv.}$ less than 0.5 kg of boron is required

RAC Design/Analysis - Silicon





- **Heat transfer analysis and geometry optimization via COMSOL**
  - Varying cavity length, insulation and gap thickness, surface reflectivities, etc.

USC-based Experiment

Further Advancement Requires Practical Understanding

Near Term Goal: Produce and maintain a molten PCM sample via concentrated solar radiation,

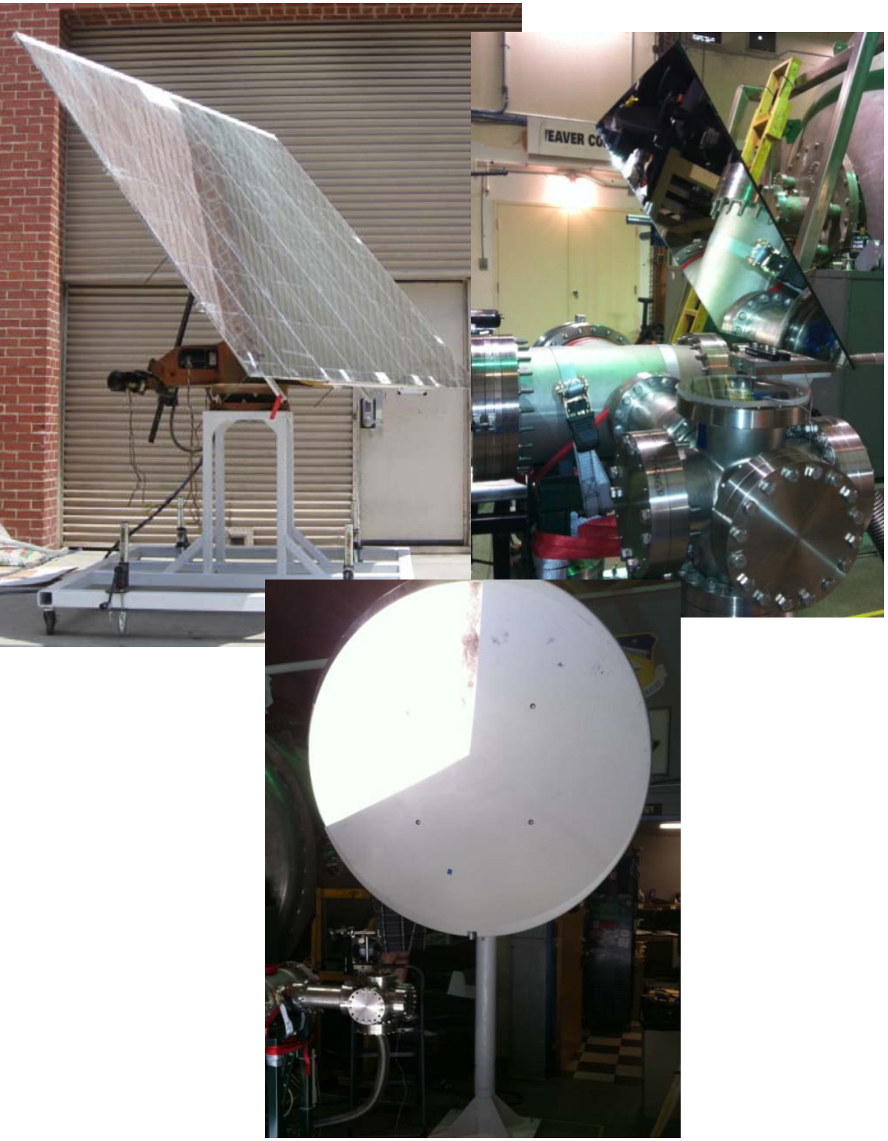
- Silicon first

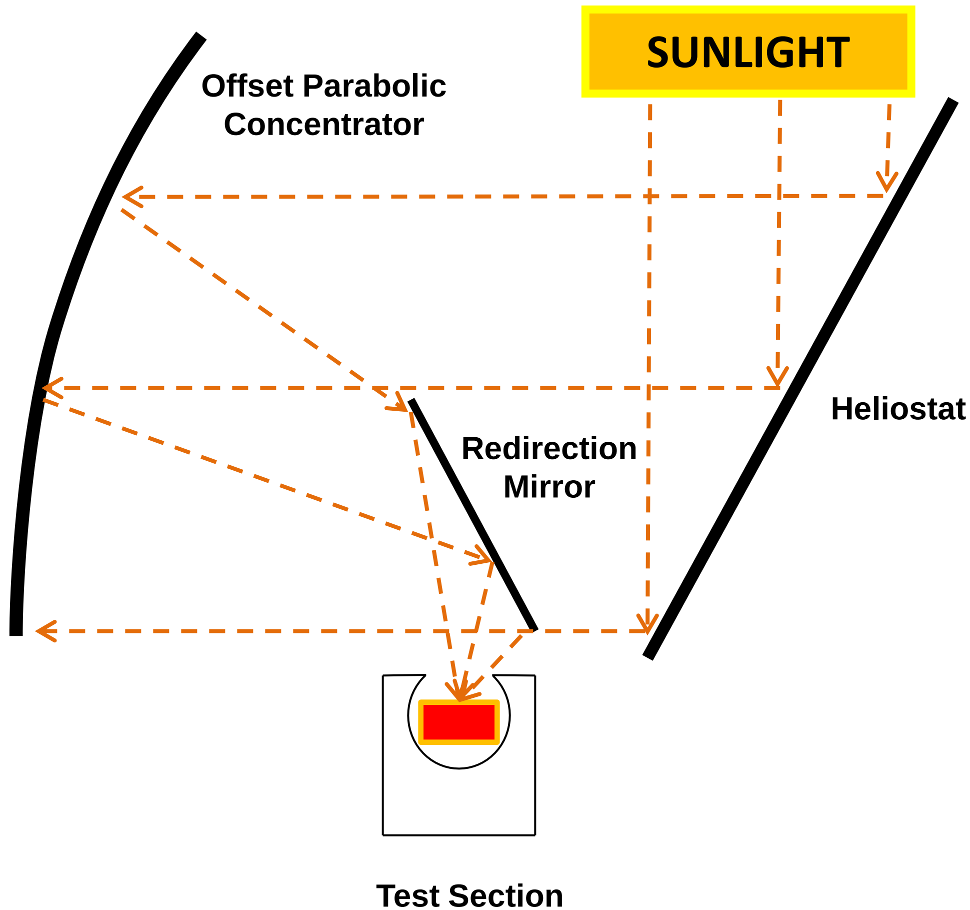
Far Term Goal: Evaluate the viability of the viability of boron-based phase change energy storage

Project to Address:

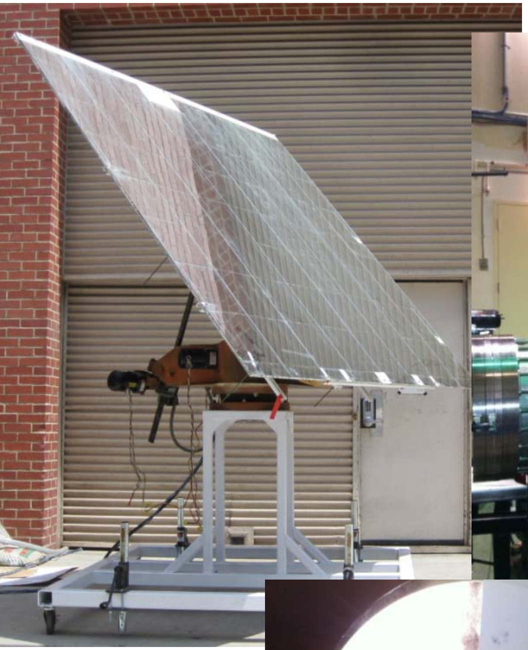
- High power solar concentration
- Material compatibilities
  - Physical/Thermal and Chemical
- Radiation shielding
- Power coupling

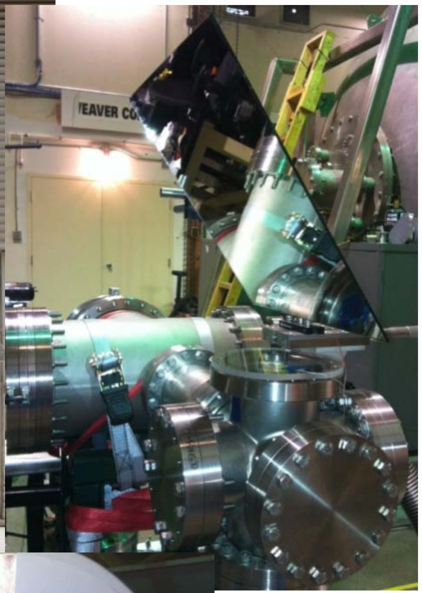
First Solar Concentration System





Solar Concentration System





- 2.4 x 2.4 m Heliostat for directiong sunlight onto parabolic concentrator dish
- Redirection mirror optimized to maintain 90% dish utilization
- Est: 1000 W delivery @ insolation of 700 W/m^2
- Overall $\eta_{transmission}$ est. at 56%
- LabView controlled heliostat accurate to ~1/8” at focal point

Intended for testing various RAC concepts, and analyzing materials compatibilities

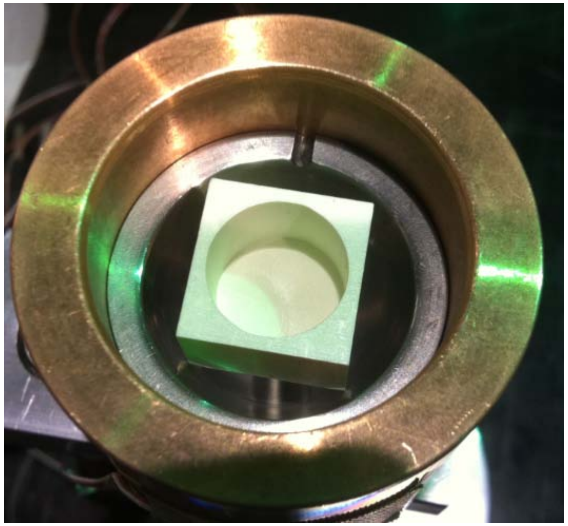
Crucible Material Considerations

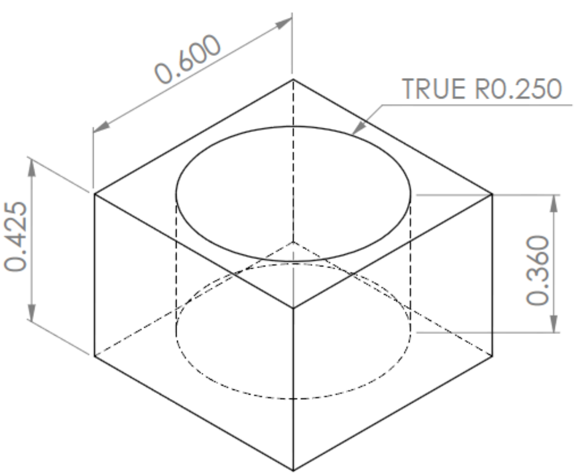
- **HBC Grade Boron Nitride**

  Lacks boric oxide binder to prevent outgassing

- **“Go-To” solution after literature review**

- **Low Reactivity with other high temp materials**

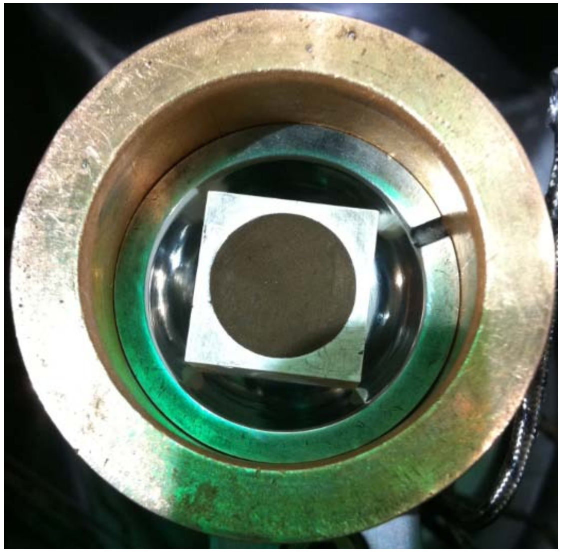




3000 K Working Temp*

$K_{th} \approx 25$ W/m-K

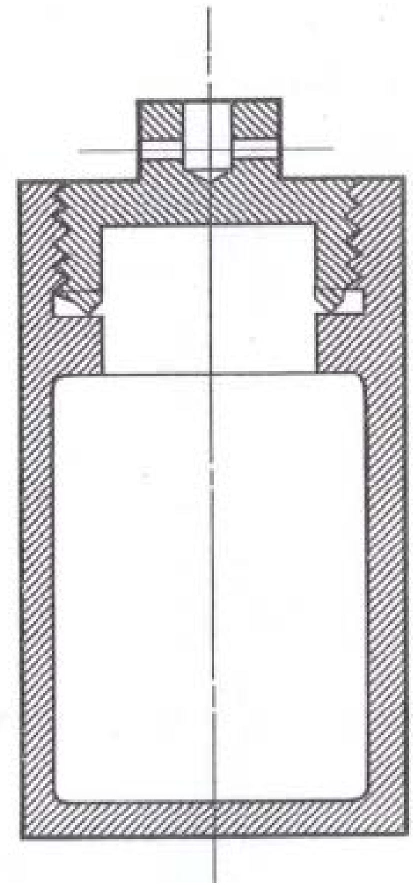
FERRO CERAMIC



Crucible Material Considerations

*BN has a strong dissociation tendency

- Experimental system must be kept at a pressure above the nitrogen equilibrium pressure
- Sources not in agreement on P_{eq}, estimated between 0.1 and 10 Torr at 2500 K
- Can be remedied by operation in a Argon or Helium Environment [Mar 1972, Kimpel & Moss 1968]
- Alternatively, BN can dissociate and self pressurize a sealed container



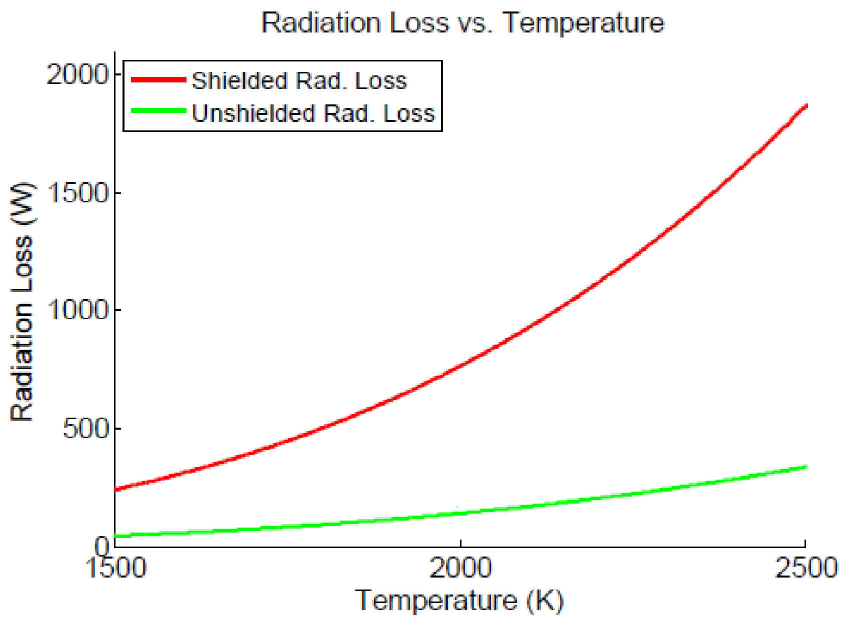
Source: Stout 1972

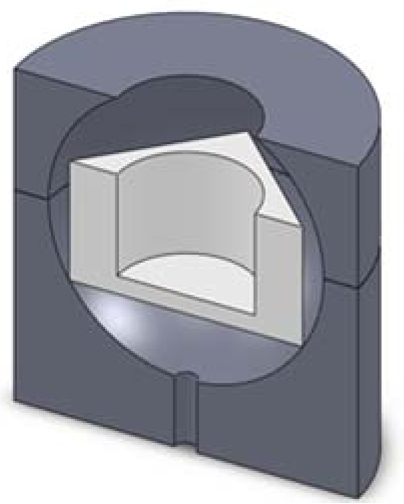
Radiation Shielding

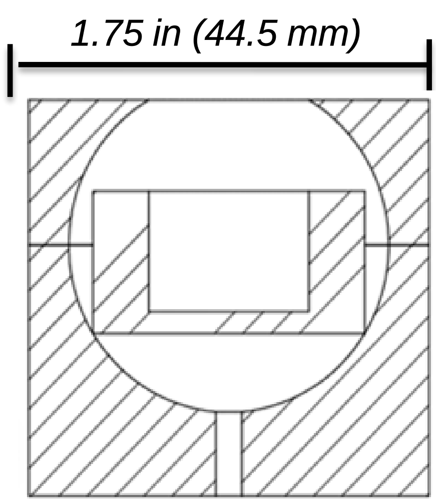
- **Without shielding, radiation loss is greater than 2300 W**

Molybdenum Radiation Shield

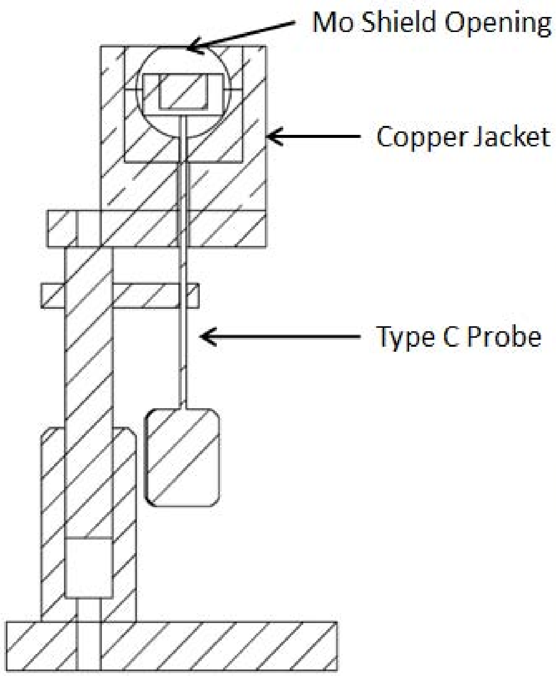
- >70% drop in radiation losses
- Spherical cavity with mirrored surface
- Total input of ~ 800 W required

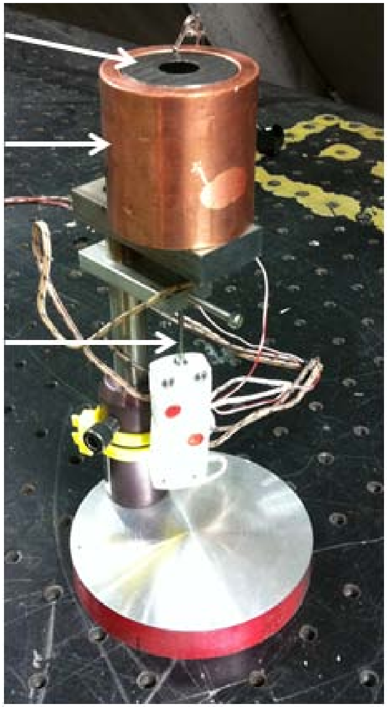






Shield Support Structure

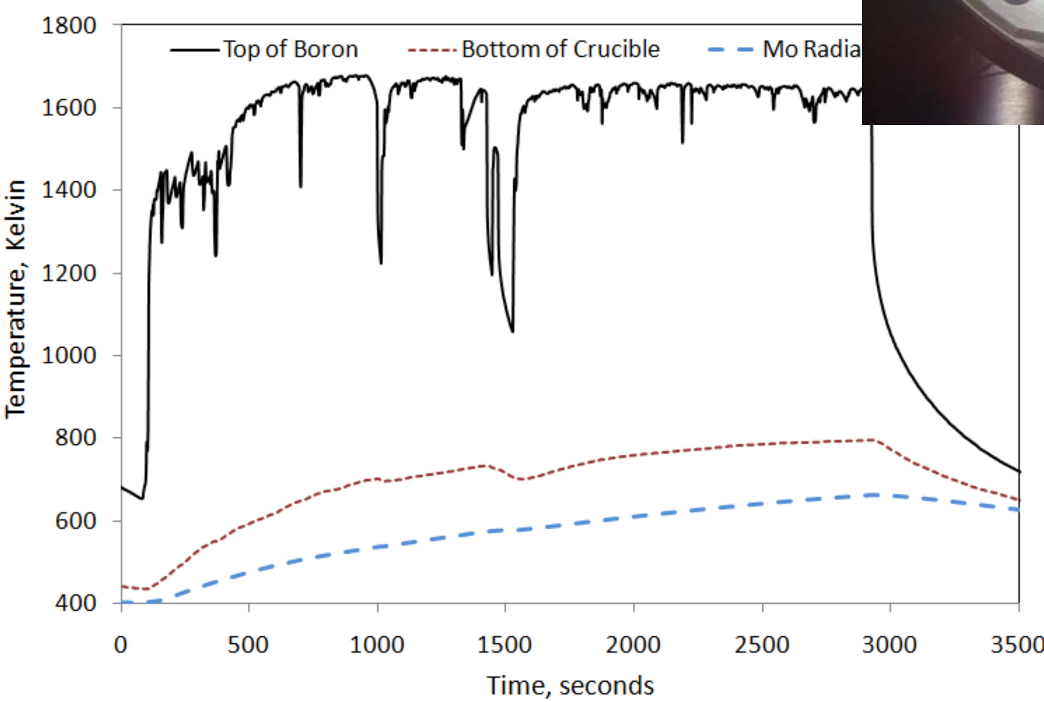


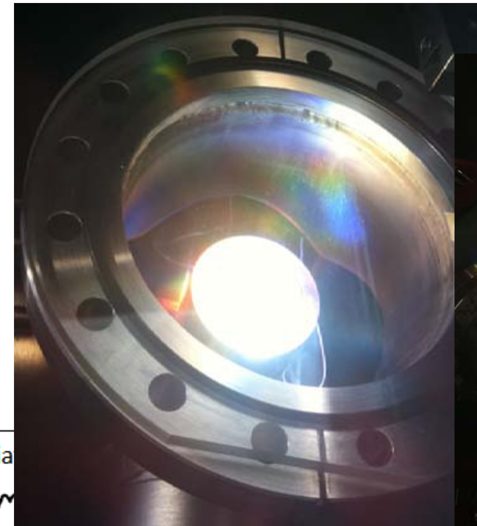


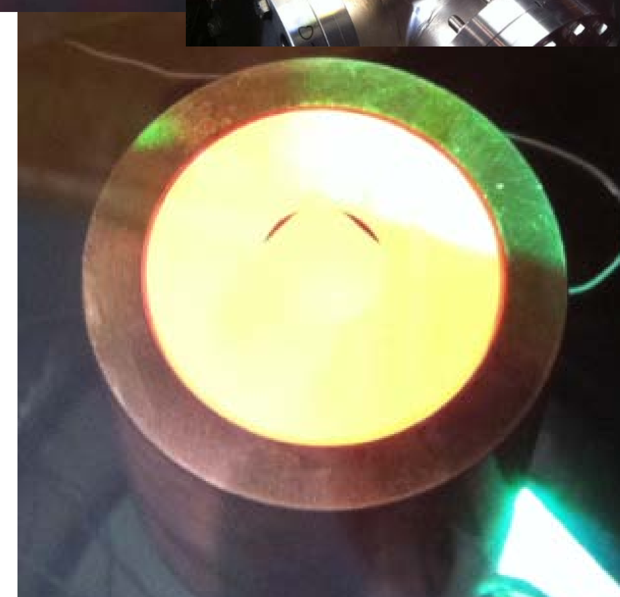
- Type C and J probes throughout
- Placed in chamber under a quartz window
- Initially designed with copper jacket; will be replaced with insulator or other design

Initial Data

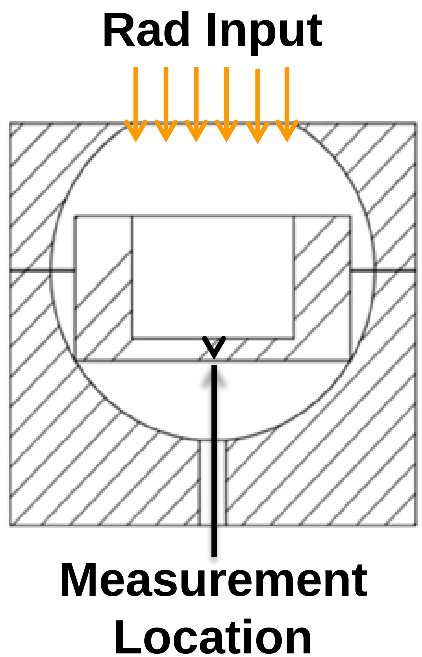
- **Testing at 10% design power level to evaluate diagnostics and system performance**
- **Indicates a significant reduction in radiation losses**







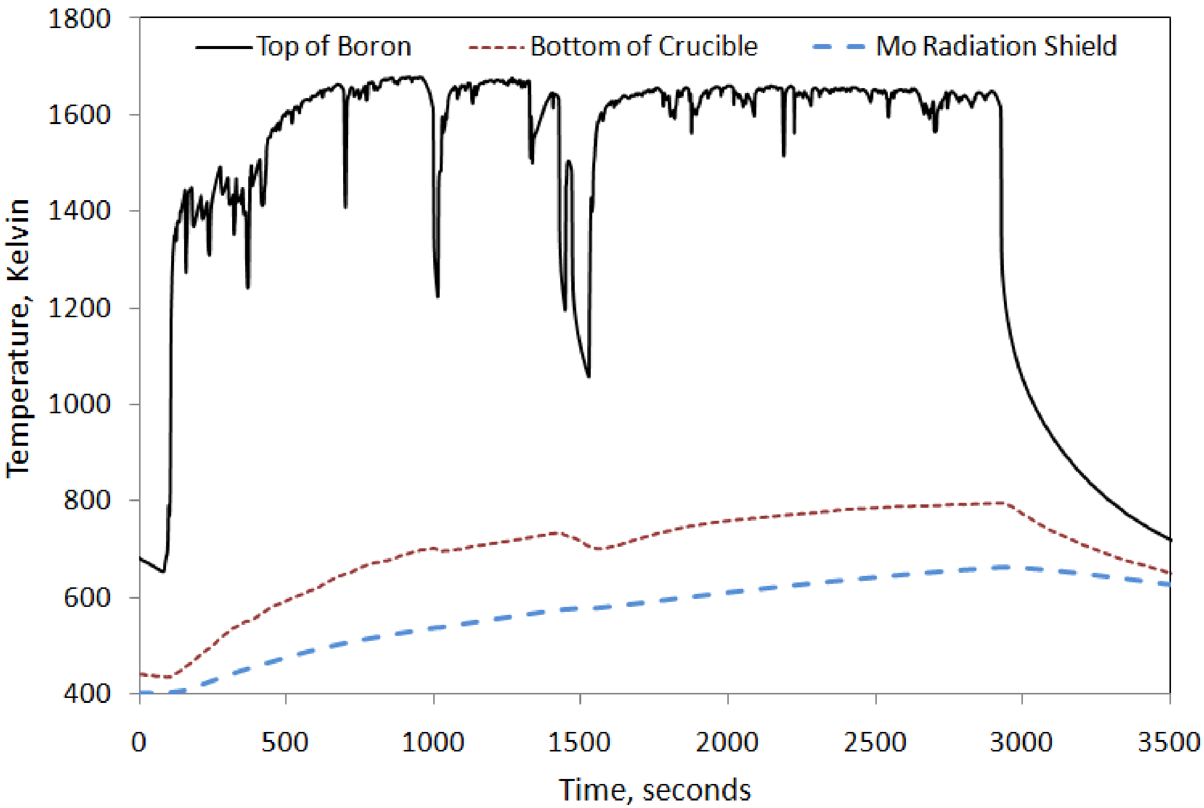
Empty and Boron Filled Crucibles

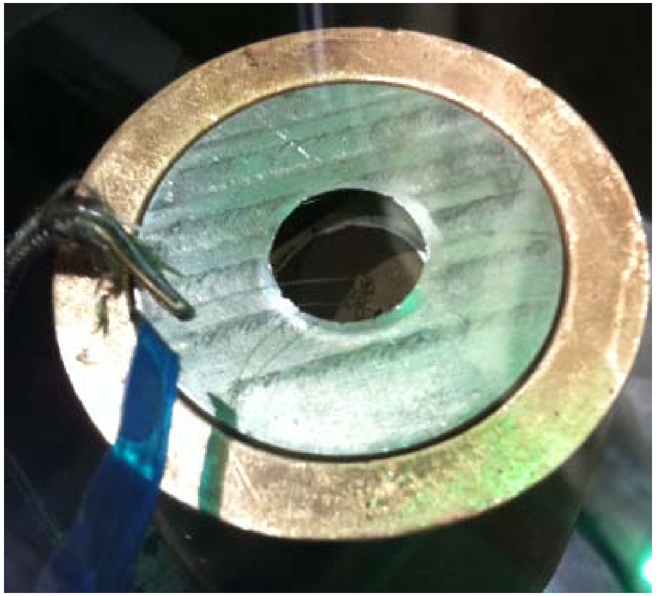


Measured Temp. ≈ 900 K

Measured Temp. ≈ 800 K

Upper Surface Measurements

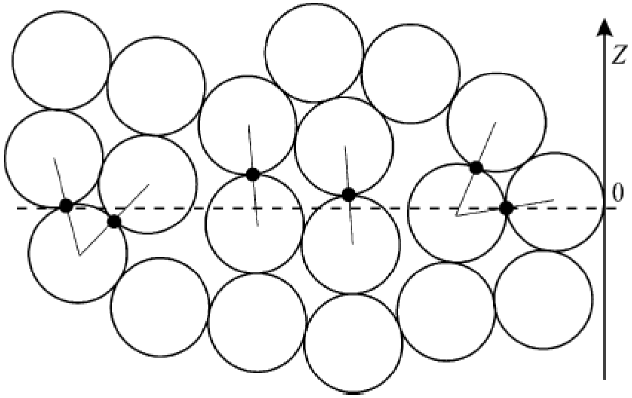




Gradient of ~ 1000 K across the crucible

Large Thermal Gradients

- **Top down radiation input approach is producing large thermal gradients**
- **Requires a design capable of distributing incoming radiation**
- **Packed boron bed and BN both have a relatively low thermal conductivity**

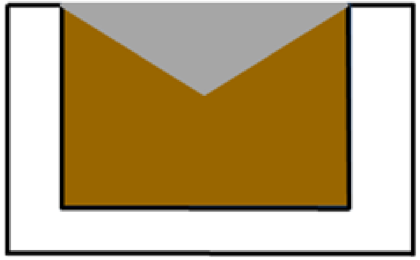


Source: Gusarov et. al

With current < 1μ particles
$k_{eff} \approx 10$ W/mK

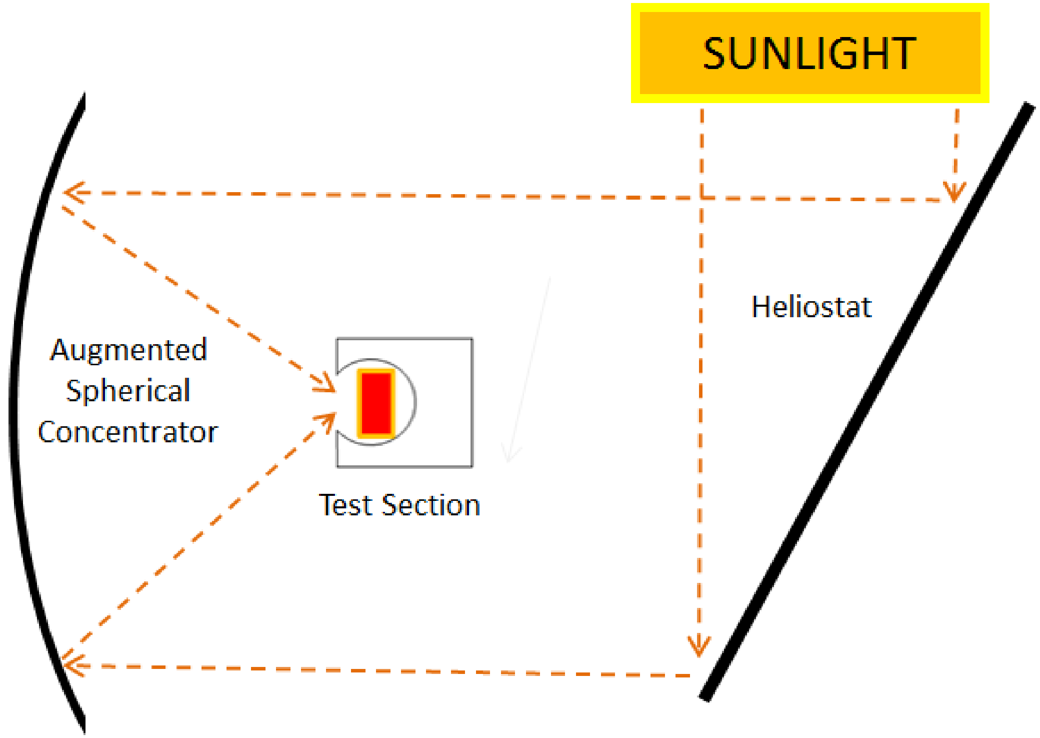
Top Layer

2nd Layer



Est. Profile

Future Concentration System



- **Long-term: concentrator consisting of smaller spherical mirror segments**
- **Near-term: 1 m^2 Fresnel lens directing light into the test cell for lower power tests (~250 Watts measured via radiative flux meter at focal point; estimated ~200 Watts delivered inside cell)**
- **Focus on silicon in the near-term**

Conclusions

- **Microsat capability can be significantly enhanced by STP augmented with high performance thermal energy storage**
  - High performance bi-modal system is required
  - Apart from high performance energy storage, many technical challenges have already been addressed
  - High temperature elemental phase change materials may meet performance requirements

- **Molten Boron as a PCM**
  - Near ideal melting / storage temperature
  - High energy storage density
  - Multiple technical challenges

Conclusions

- **USC Experimental Facility**
  - System to produce and contain molten TSM with concentrated solar radiation is under development
  - Initial data has already identified key areas of concern for the project

- **Future Work**
  - Upgrade to the solar concentration system
  - Create/contain molten silicon, analyze system
  - Work toward molten boron
  - Demonstrate and assess the viability of a molten boron based system

Questions / Comments?

Supplemental Slides

■ ■ ■ ■

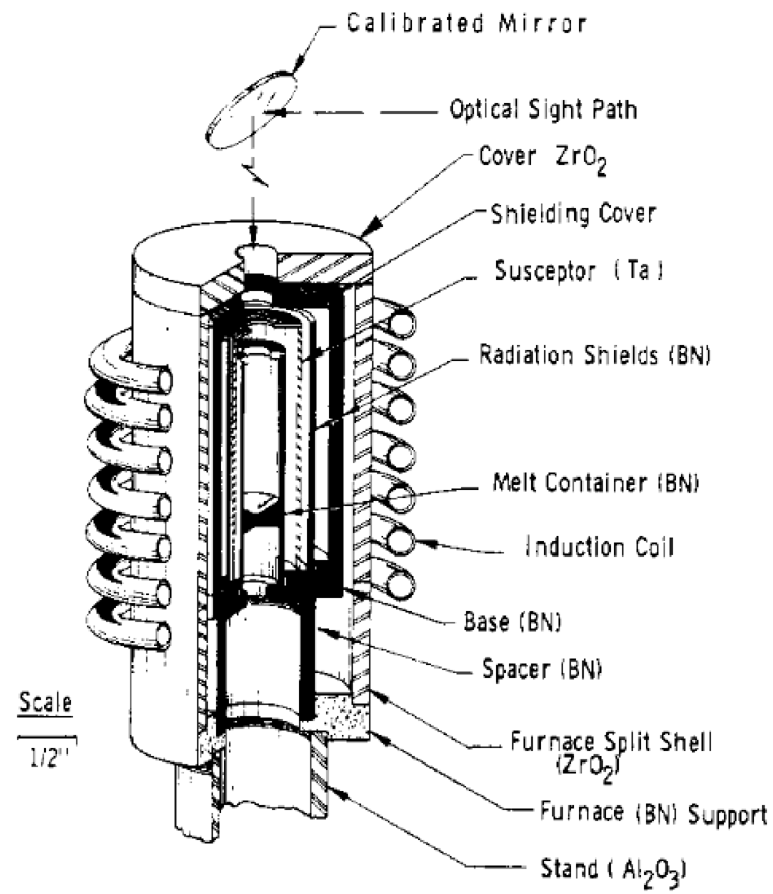
Development Requirements
PCM Containment

Container must manage long term stability and reactivity with the PCM

Tungsten, Molybdenum, Tantalum
- Limited research suggests boride formation
- Required for other system components

Graphite
- 20-25% bulk sample contamination in molten boron crucible use [Stout, 1973]
- Can attack other system materials

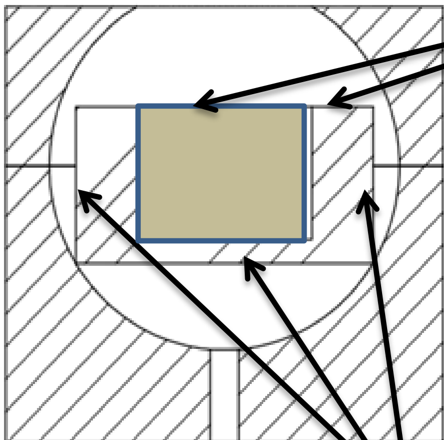
Boron Nitride
- Material of choice for molten boron testing
- Dissociation issues at high temperature



Source: Kimpel & Moss 1968

USC MBE
Rad. Shielding Assumptions

Rad loss is the radiation transferred to the shield from the crucible



Boron and Top Surface
- Modeled as if UN-SHIELDED grey body

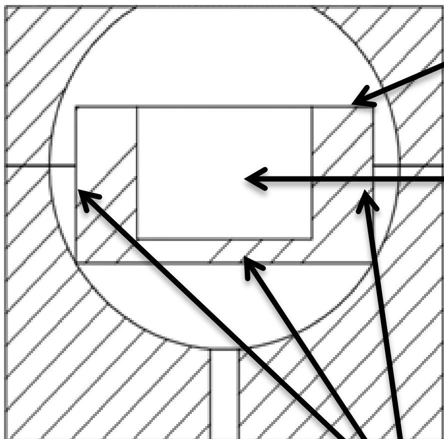
Assume an “enclosure” with shield
- These sides of the crucible have a view factor of 1 w/ Mo
- Small fraction of re-radiated radiation escapes the cavity

$$q_{12} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

- Moly is kept 200 K below crucible
- Neglect conduction through tips

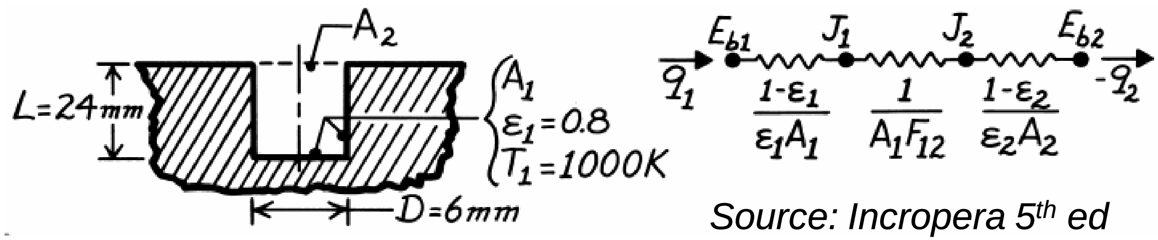
USC MBE
Rad. Shielding Assumptions

Rad loss is the radiation transferred to the shield from the crucible



Modeled as UN-SHIELDED

Modeled as an isothermal cavity



Source: Incropera 5th ed

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